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Control Method of the Three-Phase Four-Leg Shunt Active Power Filter

Li Bin*, Tong Minyong

Tianjin university of technology and education, Hexiqu, Tianjin 300222, China

Abstract

This paper presents a novel all-digital approach applied to three-phase four-wire active power filter (APF), which is made up of three-phase four-leg voltage source converters. The controller just detects the main current and DC side capacitor voltage. Calculation method of the switch duty cycle is deducted on the base of mathematics model formed. This controller has fewer measurement, higher robustness and simpler calculation as comparing to traditional controllers. Simulation verify that the APF with proposed controller can compensate the harmonics effectively.

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Keywords: active power filter, harmonic, three-phase four-leg;

1. Introduction

The application of new power electronic equipments in power grid makes the power transformation and application more flexible. But it brings serious power quality problems such as harmonic pollution, reactive power shortage, voltage fluctuations, imbalances, etc. As a traditional method for harmonic control, passive filter (PF) will be gradually replaced by new devices, due to the disadvantage that it can only filter some specific orders of harmonics and may lead to series-parallel resonance with power grid [1-4]. Active power filter (APF) has been recognized as one of the most effective means for harmonic control, reactive pollution control and power quality improvement [5-8]. Thus, it has become a new research focus in the application of power electronics technology. In this paper, by using four-bridge converter circuit structure, a new digital control method was put forward. This method just detects the

* Corresponding author. Tel.: +86-22-28221083; fax: +86-22-28111083.

E-mail address: libinfly@163.com.

system current and the dc-side voltage of the converter. Through the simple calculation of voltages, the duty cycles of each switch for the arm are obtained.

2. Theoretical Analysis

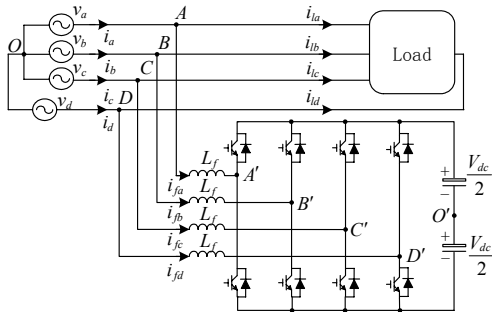


Fig. 1. Diagram of the main circuit

Fig.1 presents the circuit diagram of the three-phase four-wire active power filter. In Fig.1, i_a , i_b and i_c respectively represents the system input currents of phase A, B and C; i_d is the zero line current of system side; i_{la} , i_{lb} and i_{lc} respectively represents the load currents of phase A, B and C; i_{ld} is the zero line current of load side. The four-bridge-arm voltage source inverter is connected to the system with four series inductances and a three phase parallel load. Capacitance is used as energy storage devices to maintain a constant voltage V_{dc} of DC side. To simplify the analysis, the capacitance is divided into two equivalent capacitances. O' is set to the dc side voltage reference point. In order to express the quantities of D phase in unified way, the D phase voltage is supposed as $v_d = V_{DO}$. From the symmetry of circuit, $V_{OO'} = 0$ exists when the system runs in the steady-state. Thus, the voltage balance equation can be expressed as

$$\begin{cases} V_{AA'} = v_a - V_{A'O'} \\ V_{BB'} = v_b - V_{B'O'} \\ V_{CC'} = v_c - V_{C'O'} \\ V_{DD'} = v_d - V_{D'O'} \end{cases} \quad (1)$$

Where $V_{A'O'}$, $V_{B'O'}$, $V_{C'O'}$ and $V_{D'O'}$ respectively represent the APF's output voltages of phase A, B, C and D. Their values can be set to $\pm V_{dc}/2$ according to the switch states. When the upper leg conduction and the lower leg off, the output voltage is set to $V_{dc}/2$. In the contrast, $-V_{dc}/2$ is used. $V_{AA'}$, $V_{BB'}$, $V_{CC'}$ and $V_{DD'}$ represent the voltages of each inductance L_f .

Under the steady-state condition, by using the voltage-second balance characteristics of the inductance, there exists in one switch cycle. The aim of APF control is to make the phase currents of power grid have linear relationship with the corresponding system voltages. When this goal is achieved, the system becomes stable. Thus, in system side, the load and the active power filter can be equivalent to a resistance as

$$\begin{cases} v_a = R_s i_a \\ v_b = R_s i_b \\ v_c = R_s i_c \end{cases} \quad (2)$$

Where i_a , i_b and i_c are the fundamental components of the active power. By using the symmetrical components decomposing method, we can obtain

$$v_d = \frac{-(v_a + v_b + v_c)}{3} \quad (3)$$

From (2) and (3), we get

$$v_d = -R_s \cdot \frac{i_a + i_b + i_c}{3} \quad (4)$$

After stabilization, the DC side voltage V_{dc} is kept constant. The relationship between it and the amplitude of the grid phase voltage V_s is

$$V_{dc} = K \cdot V_s \quad (5)$$

Where K is the amplification coefficient. Combined with (2), we get

$$V_s = R_s I_s \quad (6)$$

Substituting (6) into (5), we get

$$V_{dc} = K \cdot R_s I_s \quad (7)$$

Compared the capacitor voltages with the given reference voltage, the results will be sent to PI controller, the output of the PI controller is the expected current amplitude I_s in grid side [9].

3. System Analysis

The diagram of current loop is shown in Fig.2. In which, u_f is the output voltage of the inverter; system voltage u_s and u_f are applied to the input of the inductance to get the compensation current i_f ; i_l is the load current as disturbance signal; i_s is the system current, i.e., the output of the current loop.

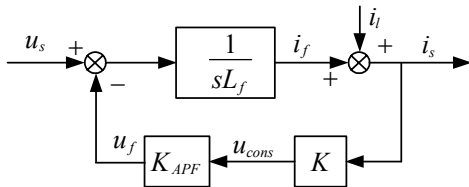


Fig. 2. Diagram of current loop

Note that the time constant of the current loop is far less than the cycle of the input voltage. Thus, the input of the control system can be regarded as a constant, namely ignoring the tracking problem between the input and the output. Here, we focus on the relationship between i_s and i_l . In Fig.2, let the input u_s is zero, we can get

$$\Phi_{I_l}(s) = \frac{s}{s + \frac{K \cdot K_{APF}}{L_f}} = \frac{s}{s + K'} \quad (8)$$

In order to improve the anti-disturbance ability of APF, larger K' in (8) should be set according to

$$K' = \frac{K \cdot K_{APF}}{L_f} \quad (9)$$

It can be concluded that when K is constant, smaller L_f is beneficial to suppress the harmonics. According this control strategy K is set as the same in (5). Considering the time delay formed by the triggering pulses in system, the feedback loop in Fig.2 should contain a delay e^{-sT_s} . Thus, bigger K' may lead the system to unstable state. In this condition, the system transfer function for the open loop in Fig.2 can be written as

$$G_l(s) = e^{-sT_s} \cdot \frac{K'}{s} \quad (10)$$

The critical stability condition of the open loop control system is

$$\begin{cases} \angle G_l(j\omega) = -\pi \\ |G_l(j\omega)| = 1 \end{cases} \quad (11)$$

From (18) and (19), the critical magnification factor for system stabilization can be get as

$$K' = \frac{\pi}{2T_s} \quad (12)$$

The critical magnification factor determines whether the system is stable and the stable margin. It is determined by the switch cycles of the control system as shown in (12). Big K' may lead system to a instable state or with small stability margin.

Fig.3 shows the diagram of the voltage loop control system.

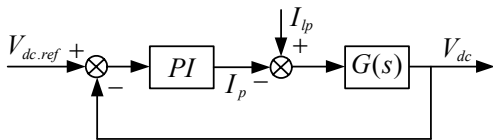


Fig.3. Diagram of voltage loop

In Fig.3, $G(s)$ represents the balance process of the inverter DC side capacitor voltage.

Since

$$P_{dc} = P_s - P_l \quad (13)$$

Where P_{dc} is the active power in DC side, P_s is the active power in grid side, and P_l is the fundamental component of active power in load side. Further, (13) can be expressed as

$$C \cdot V_{dc} \cdot \frac{dV_{dc}}{dt} = 3V_s I_p - 3V_s I_{lp} \quad (14)$$

With Laplace transformation, (14) can be written as

$$G(s) = \frac{V_{dc}(s)}{I_p(s) - I_{lp}(s)} = \frac{3V_s}{CV_{dc} \cdot s} \quad (15)$$

Thus, the closed-loop transfer function is given as

$$\Phi_V(s) = \frac{G_{PI}(s) \cdot G(s)}{1 + G_{PI}(s) \cdot G(s)} \quad (16)$$

Where $G_{PI}(s)$ represents the PI controller in Fig.3, it can be expressed as

$$G_{PI}(s) = k_p + \frac{k_I}{s} \quad (17)$$

Where k_p is the proportional coefficient, and k_I is the integral coefficient. By substituting (17) and (15) into (16), the closed-loop transfer function of the voltage loop is

$$\Phi_V(s) = \frac{k_p s + k_I}{\frac{CV_{dc}}{3V_s} s^2 + k_p s + k_I} \quad (18)$$

4. Simulation Results

The proposed three-phase parallel type APF control algorithm is performed by Matlab/Simulink tools. Table 1 show the parameters used in simulation.

Table1. System parameters for simulation

Parameter	Value
And an entry phase Voltage RMS(V)	100
Switching frequency(Hz)	50
Voltage frequency(Hz)	9600
Inductance(Mh)	0.4
DC link capacitor(μF)	5000
DC link voltage(V)	220

Fig.4 presents the three phase currents waveform. Fig. 4(a) shows that the three phase currents are asymmetric with obvious waveform distortion before compensation. Fig.4 (b) illustrates that the proposed algorithm have good compensation effect on current asymmetry and low-order harmonics.

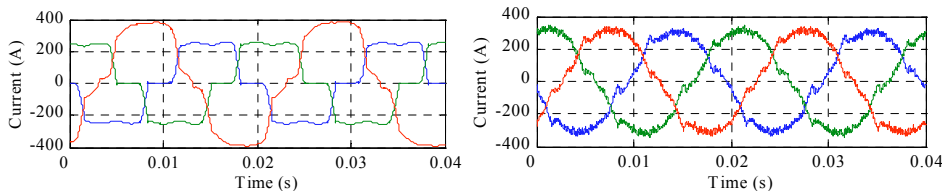


Fig. 4. (a) three-phase currents before compensation; (b) three-phase currents after compensation

5. Conclusions

A simple and easy implemented control method for three-phase four leg parallel active power filter is put forward in this paper. The simulations show that the proposed method can compensate harmonics and asymmetries of the three-phase four leg system. This method owns the advantages such as fewer sensing quantities, without any computation of harmonic current, simple control algorithm, and easy to be realized in digital control. The simple algorithm can reduce the complexity and the cost of the control circuit system.

Acknowledgements

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